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Why the observed jet quenching at RHIC is due to parton energy loss

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Abstract

Significant jet quenching in central Au + Au collisions has been discovered at RHIC. This Letter provides theoretical arguments and lists experimental evidence that the observed jet quenching at RHIC is due to parton energy loss instead of hadron rescattering or absorption in a hadronic medium. These include: (1) hadron formation time based on the uncertainty principle, (2) p_T dependence and (3) centrality dependence of the observed jet quenching, (4) jet-like leading hadron correlations (5) high-p_T azimuthal anisotropy and (6) experimental data from Pb + Pb collisions at SPS and $e + A$ collisions. Direct measurements of the parton energy loss in the direction of a triggered high-p_T hadron and the medium modified fragmentation function on the back-side are proposed to further verify the partonic nature of the observed jet quenching. The importance of jet quenching studies at lower energies at RHIC is also discussed.

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1. Introduction

More than a decade after the original proposal [1,2] of jet quenching due to radiative parton energy loss, conclusive experimental evidence has been found in central Au + Au collisions at the relativistic heavy-ion collider (RHIC) not only from the suppression of high-p_T single inclusive hadron spectra [3–5] but also the suppression of back-side jet-like correlations [6]. The latter provides direct evidence for medium modification of the parton fragmentation functions [7]. More recent results of d + Au collisions [8–10] further prove that the observed jet quenching is due to final-state interactions with the produced medium. Initial-state scatterings in cold nuclei only broaden the initial transverse momentum, leading to the Cronin enhancement of intermediate high-p_T hadron spectra as was first predicted for $p + A$ collisions at RHIC [11].

The original proposal of jet quenching in a dense (or normal) nuclear medium [1,2] was based on the idea that radiative energy loss during the propagation of an energetic parton must suppress the leading hadron distributions inside a jet. This leads to medium modification of the jet fragmentation functions [7] and suppression of the high-p_T hadron spectra in high-energy heavy-ion collisions. Such medium-induced radiative parton energy loss has since been

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studied in detail and in many different approaches [12–18] in QCD that include the non-Abelian Laudau–Pomeranchuck–Migdal (LPM) interference effect. The energy loss was found to be proportional to the gluon density of the medium. It was further predicted that jet quenching due to parton energy loss should also lead to the azimuthal anisotropy of high-p_T hadron spectra in non-central heavy-ion collisions [19], which has been observed [20] at RHIC.

Phenomenological studies of hadron spectra based on parton energy loss have found that the observed suppression of high-p_T single hadron spectra implies large parton energy loss or high initial gluon density [18,21–24]. The same parton energy loss is also found to reproduce the observed suppression of back-side correlation [25,26] and the high-p_T azimuthal anisotropy [26,27]. Most importantly, the calculated centrality dependences of the suppression of both single hadron spectra and back-side correlation agree very well with the experimental measurements [26]. The deduced initial gluon density at an initial time $\tau_0 = 0.2\ \mathrm{fm}/c$ is found to be about 30 times of that in a normal nuclear matter [24,26]. If the transverse energy per particle is 0.5 GeV [28], the above gluon density will correspond to an initial energy density of $\epsilon = 15\ \mathrm{GeV/fm}^3$, which is about 100 times of the energy density in a cold nuclear matter. In addition, the measured large azimuthal anisotropy for soft hadrons is found to saturate the hydrodynamic limit [29,30]. These experimental results all point to an initial medium that is strongly interacting and has a large initial pressure gradient. Within our current understanding of QCD, such a strongly interacting medium with about 100 times normal nuclear energy density can no longer be a normal hadronic matter.

The aforementioned analyses of RHIC data on jet quenching are all based on a picture in which partons propagating through the dense medium lose energy first and then hadronize outside in the same way as in the vacuum. It is reasonable to ask whether leading hadrons from the jet fragmentation could have strong interaction with the medium and whether hadron absorption could be the main cause for the observed jet quenching. This Letter will provide arguments against such a scenario in detail and list experimental evidence that the observed patterns of jet quenching in heavy-ion collisions at RHIC can *only* be the consequences of parton energy loss, not hadronic absorption.

2. Hadron formation time

Fragmentation of a parton into hadrons involves mainly non-perturbative physics in QCD and thus is not calculable within perturbative QCD (pQCD). One can, nevertheless, use pQCD to calculate the evolution of the fragmentation process due to short distance interaction when the virtuality of the parton is larger than $Q_0 \sim 1$ GeV. Such perturbative processes can take place over a period of time,

$$\tau_{\mathrm{DGLAP}} \sim 2\sum_i \frac{Ez_i(1-z_i)}{Q_i^2} \gtrsim 2\frac{Ez_0(1-z_0)}{Q_0^2}, \qquad (1)$$

where the sum is over gluon emission, and Q_i and z_i are the virtualities and fractional energies of the intermediate partons between each successive emission until Q_0 is reached. Afterwards, the non-perturbative processes of hadronization take place. One scenario of the non-perturbative process is that the produced partons (quarks and gluons) will recombine into the final hadrons. The hadron formation time can be considered as the time for partons to build up their color fields and develop the hadron wave function. According to the uncertainty principle, such a formation time in the rest frame of the hadron can be related to the hadron size R_h. In the laboratory frame, the hadron formation time is then [31]

$$\tau_f \sim R_h \frac{E_h}{m_h}. \qquad (2)$$

For an $E_h = 10$ GeV pion, this amounts to $\tau_f \sim$ 35–70 fm/c for $R_h = 0.5$–1 fm.

In some dipole models of hadronization [32], the quarks and anti-quarks from gluon splitting are assumed to combine into color singlet dipoles which will become the final hadrons. The hadron formation time is then assumed to be just the formation time for the gluon emission, ignoring the time of quark and anti-quark production and the time for dipoles to grow to the normal hadron size. Even if one considers this alternative hadronization process as successive emission of hadrons by the fragmenting jet, a hadron carrying a fraction z of the parton energy will take

$$\tau_f \sim \frac{2E_h(1-z)}{k_T^2 + m_h^2} \qquad (3)$$

to be produced, where $k_T \sim \Lambda_{\mathrm{QCD}}$ is the intrinsic transverse momentum of the hadron. As we will show later, a 10 GeV hadron comes from a parton with an average energy $E = 16.5$ GeV in $p + p$ collisions at RHIC, thus an average $\langle z \rangle = 0.6$. Using $\Lambda_{\mathrm{QCD}} = 0.2$ GeV, the formation time for a 10 GeV pion is then $\tau_f \sim 40$ fm$/c$.

Though the above numbers can only serve as order-of-magnitude estimates, they are still much longer than the typical medium size or the lifetime of the dense medium in heavy-ion collisions at RHIC. Furthermore, the above estimates are for hadronization in vacuum only. Medium interaction with the fragmenting partons will only increase the hadron formation time. Certainly, in the extreme case, the hadron can never be formed inside a deconfined medium due to color screening and the formation time should never be shorter than the lifetime of a quark–gluon plasma.

3. Momentum dependence of hadron suppression

The most striking feature of the observed jet quenching manifested in the suppression of high-p_T hadrons is the almost flat p_T dependence of the suppression at high p_T [3,4]. The empirical total energy loss has to have a linear energy dependence in order to describe such a p_T dependence [22,23]. This runs directly opposite to the trend of hadronic absorption or rescattering. Since the hadron formation time is proportional to the hadron or jet energy, the total effective energy loss due to hadron rescattering or absorption should decrease with energy, unless the energy dependence of the hadronic energy loss per unit distance is stronger than a quadratic dependence. Such a quadratic or stronger energy dependence of the energy loss can never be allowed in any physical scenario.

For elastic scatterings, the energy loss of a pion per scattering is $\Delta E_{\mathrm{el}} \approx E_\pi(1 - \cos\theta_{\mathrm{cm}})/2$, where θ_{cm} is the scattering angle in the center of mass frame. The averaged elastic energy loss can be estimated as

$$\frac{dE_{\mathrm{el}}}{dx} = \left\langle \int dt\, \frac{d\sigma}{dt} E_\pi \frac{-t}{s} \rho_h \right\rangle \approx \frac{\sigma_0}{B} \left\langle \frac{\rho_h}{\omega_h} \right\rangle, \tag{4}$$

which has a very weak energy dependence. Here $t \approx -s(1-\cos\theta_{\mathrm{cm}})/2$, $s \approx 2E_\pi\omega_h$ and $\langle\cdots\rangle$ is the thermal average over hadron energy ω_h with density $\rho_h(\omega_h)$. We have considered only the dominant t-channel when $\sqrt{s}$ is much larger than the π–h resonance mass and $d\sigma/dt$ can be described by its geometrical form $d\sigma/dt = (\sigma_0 B)\exp(tB)$, with $B/\sigma_0 \approx 0.3$ according to the observed geometrical scaling property of high energy hadron collisions for $\sqrt{s} < 100$ GeV [33]. Here, σ_0 is assumed to be the total cross section. Normally, elastic cross section is about 17% of the total cross section. This elastic energy loss is also related to the transverse momentum broadening,

$$\left\langle \frac{q_T^2}{\lambda} \right\rangle \approx \frac{\sigma_0}{B} \langle \rho_h \rangle. \tag{5}$$

For a pion gas at $T \sim 150$ MeV, the elastic energy loss is very small, about 0.036 GeV/fm, independent of the pion's energy. The corresponding transverse momentum broadening will be also very small. The energy loss due to inelastic π–h scattering is difficult to estimate. However, it should not have a linear energy dependence, according to the estimate based on the uncertainty principle [34], taking into account the LPM interference effect. Therefore, the energy loss due to hadronic interaction should have an energy dependence weaker than a linear dependence. Hadronic rescattering or absorption, with the energy dependence of the formation time, cannot give rise to the observed flat p_T dependence of the hadron suppression as shown in Fig. 1(a).

In deeply inelastic eA scattering (DIS) off nuclei, a quark jet propagating through the normal nuclear matter should also suffer energy loss leading to the suppression of its leading hadrons. Theoretical calculations [17] give a logarithmic energy dependence of the parton energy loss, which leads to a hadron suppression factor that will increase with the quark energy. As shown in Fig. 1(b), the suppression of leading hadrons as measured by HERMES experiment [35] clearly disappears as the initial quark energy is increased. The calculation of modified parton fragmentation functions due to parton rescattering and gluon bremsstrahlung [18,36], as shown by the solid lines, agrees with the data very well. Though the data can also be explained [37] as a consequence of the hadron absorption, the deduced short formation time is not consistent with the estimate in Section 2. The hadron suppression in the central Au + Au collisions at RHIC, on the other hand, are almost constant at high p_T as shown in Fig. 1(a). This is hard to understand from the original theoretical calculations of parton energy loss, since the results only depend on the gluon density, whether in a cold or hot medium. The differ-

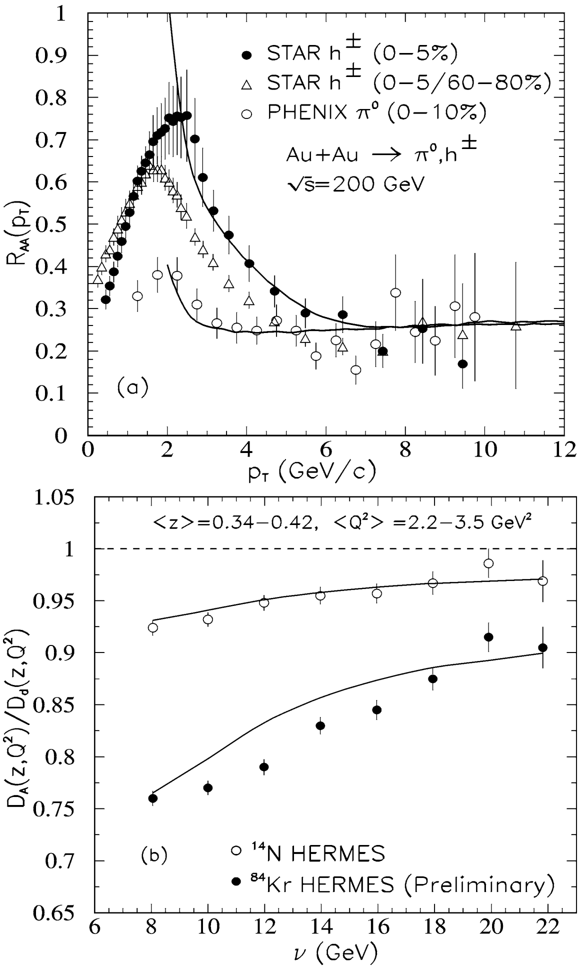

Fig. 1. The suppression factor for (a) single inclusive hadron spectra in central Au + Au collisions and (b) deeply inelastic scattering off nuclear targets. Solid lines are theoretical calculations with parton energy loss and modified fragmentation functions. Data are from PHENIX [3], STAR [4] and HERMES [35].

ent energy dependences in DIS and heavy-ion collisions could point to the effect of absorption of thermal gluons from a thermal bath, which only exists in heavy-ion collisions but is absent in DIS. This detailed balance between gluon emission and absorption in a hot medium increases the energy dependence of the net energy loss [38]. The solid lines in Fig. 1(a) are calculations based on a parameterization of parton energy loss that includes the effect of detailed balance. Calculations shown in Fig. 1(b) as solid lines for DIS only include induced gluon radiation in cold nuclei.

4. Centrality dependence of hadron suppression

This Letter will not describe the details of the calculation of single hadron and dihadron spectra in heavy-ion collisions, but refer readers to Ref. [26]. It is, however, important to point out that the effective total parton energy loss in a dynamic system is proportional to a path integral of the gluon density along the propagation trajectory. According to recent theoretical studies [18,27,39],

$$\Delta E \approx \left\langle \frac{dE}{dL} \right\rangle_{1d} \int_{\tau_0}^{\tau_0+\Delta L} d\tau \, \frac{\tau - \tau_0}{\tau_0 \rho_0} \rho_g(\tau, b, \vec{r} + \vec{n}\tau), \quad (6)$$

where ρ_0 is the averaged initial gluon density at τ_0 in a central collision, and $\langle dE/dL \rangle_{1d}$ is the average parton energy loss over a distance R_A in a 1-dimensional expanding medium with an initial uniform gluon density ρ_0. The corresponding energy loss in a static medium with a uniform gluon density ρ_0 over a distance R_A is $dE_0/dL = (R_A/2\tau_0)\langle dE/dL \rangle_{1d}$ [18]. The gluon density $\rho_g(\tau_0, r)$ is assumed to be proportional to the transverse profile of participant nucleons, which is consistent up to 30% with the measured charged hadron multiplicity [40,41].

The calculated centrality dependence of the single hadron suppression in Au + Au collisions agrees very well with the experimental measurements, as shown in Fig. 2. The centrality dependence of the back-side suppression is also in excellent agreement with the data [26]. These are the consequences of the centrality dependence of the averaged total energy loss in Eq. (6) and the surface emission of the surviving jets. Jets produced around the core of the overlapped region are strongly suppressed, since they lose the largest amount of energy.

On the other hand, if the finite hadron formation time were shorter than the medium size in the most central collisions and jet quenching were only caused by the subsequent rescattering or absorption of the leading hadrons, one should expect a more rapid disappearance or reduction of jet quenching when the medium size becomes smaller than the hadron formation time in non-central Au + Au collisions. This is clearly absent in the observed centrality dependence.

The large suppression of single hadron spectra, about a factor of 5, in the most central Au + Au collisions can actually lead to a strong constraint on

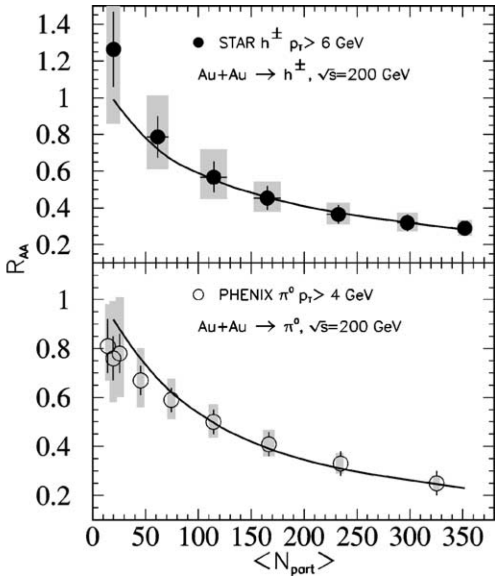

Fig. 2. The centrality dependence of the measured single inclusive hadron suppression [3,4] at high p_T as compared to theoretical calculation with parton energy loss.

the hadron formation time if no parton energy loss is allowed. One can take the most extreme scenario: there is no jet attenuation before a finite hadron formation time τ_f and every hadron is absorbed if it is still inside the medium at the formation time. The suppression factor is then determined by the ratio of the volume of the outer layer with a width τ_f and the total overlapping volume. Here one neglects the finite transverse flow velocity in the early time. With a hard-sphere nuclear geometry, one finds that a factor of 5 suppression would require a formation time shorter than 2 fm/c, which is hard to reconcile with the theoretical estimate for a 10 GeV pion.

5. Jet-like hadron correlation

Perhaps the most discriminating experimental evidence against jet quenching via hadron rescattering or absorption comes from two-particle correlations. Jet structure of azimuthal correlations of leading hadrons is clearly seen in RHIC experiments and it is the same in $p + p$, $d +$ Au and peripheral Au + Au collisions [6,9]. It consists of one peak in the near-side of the triggered hadron and another in the back-side. As one increases the centrality in Au + Au collisions, the back-side correlation is significantly suppressed just as the single hadron spectra. The near-side correlation, on the other hand, remains the same as in $p + p$ and $d +$ Au collisions. This is clear evidence that jet hadronization takes place outside the dense medium with a reduced parton energy. On the other hand, let us suppose that the leading and sub-leading hadrons from jet fragmentation are produced inside the dense medium, hadron rescattering and absorption will certainly change the near-side correlation as a function of centrality both in strength and shape, if they are responsible for the suppression of single hadron spectra and back-to-back correlations. Barring corrections due to trigger bias toward surface emission, the same-side correlation should be suppressed as much as the single hadron spectra, were the suppression caused by hadron absorption. This is clearly not seen in the data. This measurement of leading and subleading hadron correlation can also be employed in the DIS experiment to study hadron formation. When the initial quark energy is sufficiently small, hadrons will be formed inside the nucleus and the jet profile will be modified due to hadronic rescattering or absorption.

It should be stressed that the above argument is only true when the transverse momenta of the leading and subleading hadrons are close to each other. This is to ensure that both of them come from hadronization of the leading parton. If the subleading hadron is very soft, then contribution from emitted gluons induced by bremsstrahlung can become important. These soft hadrons will then have different correlation and azimuthal profile from that in pp collisions.

Because of the trigger bias, the triggered high-p_T hadrons mainly come from jets that are produced near the surface of the overlapped region. However, on the average the original jet should lose a finite amount of energy. In the pQCD parton model, one can calculate the average energy of the initial jet that, after rescattering and induced bremsstrahlung, eventually produces a leading hadron with transverse momentum p_T^{trig}. Shown in Fig. 3 are the averaged jet energies minus p_T^{trig} as functions of $\langle N_{\mathrm{part}}\rangle$ for different values of p_T^{trig}. The averaged $\langle z\rangle = p_T^{\mathrm{trig}}/\langle E_T\rangle^{\mathrm{jet}}$ in $p + p$ collisions is found to be about 0.6–0.7, with the triggered hadron carrying most of the jet energy. Here, $\langle E_T\rangle^{\mathrm{jet}}$ is the parton energy before fragmentation averaged over

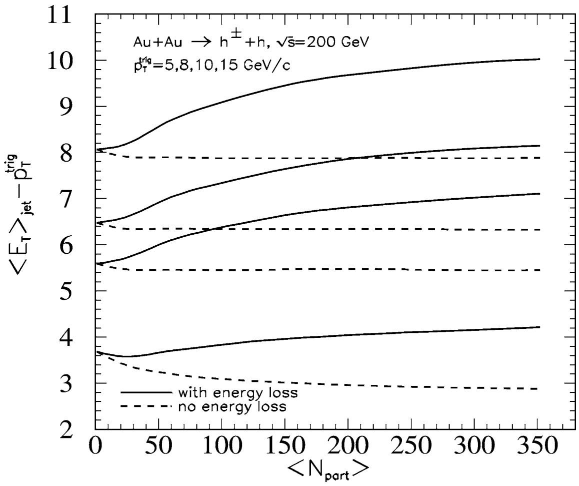

Fig. 3. The average transverse energy $\langle E_T\rangle^{\text{jet}}$–$p_T^{\text{trig}}$ of the initial partons that produce a final hadron with p_T^{trig} as a function of $\langle N_{\text{part}}\rangle$ for different values of p_T^{trig} (increasing from lower to top lines). Solid lines are for Au + Au collisions with finite parton energy loss that describes the inclusive hadron suppression and dashed lines for calculation without parton energy loss (but with initial multiple scatterings).

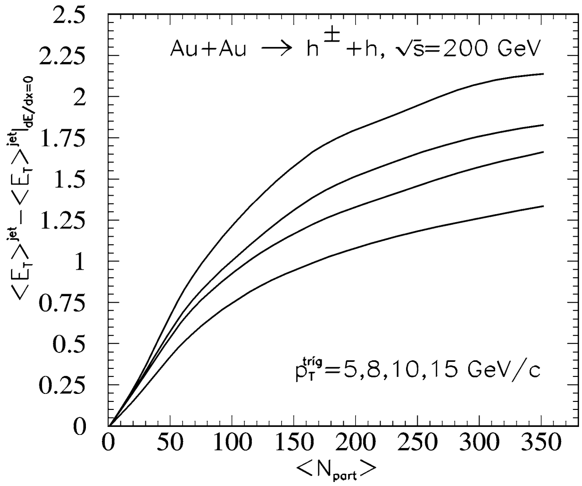

Fig. 4. The average energy loss for partons that produce a final hadron with p_T^{trig} in Au + Au collisions.

jet production cross sections and fragmentation that always give a leading hadron with $p_T = p_T^{\text{trig}}$. In heavy-ion collisions, the jet loses some amount of energy before it hadronizes. Therefore, it has to have higher initial energy than in $p + p$ collisions in order to produce a leading hadron with the same p_T^{trig}. The extra amount of energy increases with centrality as shown by the solid lines.

Note that $\langle E_T\rangle^{\text{jet}}$ evaluated here is the transverse energy in the center of mass frame of the two colliding partons. Initial multiple scattering will increase the initial parton transverse momentum leading to the observed Cronin enhancement of high-p_T single hadron spectra in d + Au collisions [8–11]. The trigger bias then leads to smaller values of $\langle E_T\rangle^{\text{jet}}$ in Au + Au collisions without energy loss than in $p + p$ for a fixed p_T^{trig} as shown by the dashed lines in Fig. 3. The difference between solid and dashed lines should then be the averaged energy loss for a jet that survived multiple scattering and gluon bremsstrahlung and produces a leading particle with p_T^{trig}. This is shown in Fig. 4 as a function of $\langle N_{\text{part}}\rangle$. In the most central collisions, jets that produce a leading hadron at $p_T^{\text{trig}} = 5$–15 GeV/c lose about 1.4–2.2 GeV energy on the average.

It is important to emphasize here that the above calculated average jet energy $\langle E_T\rangle^{\text{jet}}$ is the initial parton energy associated with a leading hadron with $p_T = p_T^{\text{trig}}$ in a leading order pQCD calculation. Such a jet energy is difficult to measure in heavy-ion experiments using the conventional jet reconstruction method because of the large background and its fluctuation. One can, however, make an experimental measurement that will be close to the theoretical definition of the jet energy. One can define a cone (in rapidity and azimuthal angle) along the direction of the triggered leading hadron, and then measure the transverse energy carried by all hadrons inside the cone average over all triggered events. One can choose the cone size, for example, to be $|y| < 0.5$ and $|\phi| < \pi/4$. The average background energy, which should be subtracted, can be determined as the averaged energy carried hadrons in the same amount of phase space between an azimuthal angle $\pi/4$ to $3\pi/4$ relative to the triggered hadron. This corresponds to the region between the two back-to-back jets. The energy determined in such a way will depend on jet cone size. Since hadrons from hadronization of the emitted gluons could be very soft, one should use a momentum cut-off as small as possible in order to make sure all hadrons from the jet fragmentation are included. The angular broadening of jets [42] in principle could also influence the value of the jet energy determined this

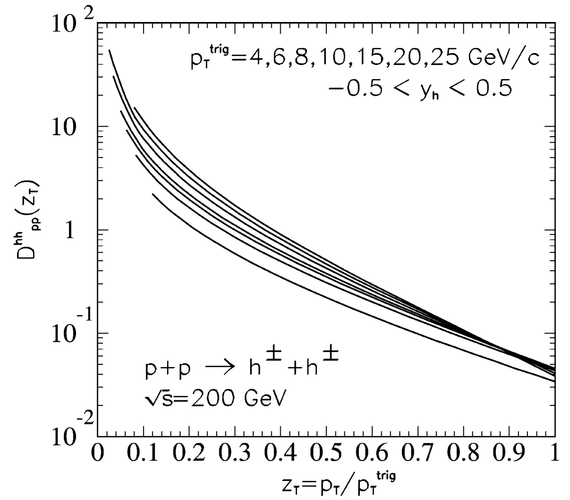

Fig. 5. Hadron-triggered effective fragmentation function in $p+p$ collisions from pQCD parton model calculation for different values of $p_T^{\rm trig}$ (with increasing values from lower to top solid lines).

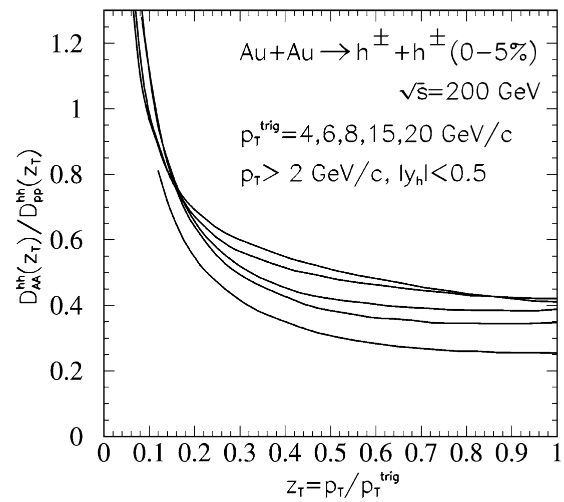

Fig. 6. The medium modification of the hadron-triggered fragmentation function, defined as the ratio of hadron-triggered fragmentation functions in central Au + Au and $p+p$ collisions for different values of $p_T^{\rm trig}$ (increasing from lower to top solid lines).

way [43]. So one should keep in mind these errors when interpreting the experimental measurements.

On the back-side of the triggered hadrons, one can define a hadron-triggered effective fragmentation function [26],

$$D^{h_1h_2}\big(z_T, p_T^{\rm trig}\big) = p_T^{\rm trig}\frac{d\sigma_{AA}^{h_1h_2}/dp_T^{\rm trig}\,dp_T}{d\sigma_{AA}^{h_1}/dp_T^{\rm trig}}, \tag{7}$$

for associated hadron h_2 with p_T in the back-side direction of h_1 with $p_T^{\rm trig}$, where $z_T = p_T/p_T^{\rm trig}$. The back-side direction is defined by $|\Delta\phi - \pi| < \pi/2$. This way, one can ensure that the jet cone includes most of the soft hadrons. This is equivalent to finding remnants of lost jets in heavy-ion collisions [44]. Shown in Fig. 5 are the hadron-triggered fragmentation functions in pp collisions. The differences between different values of $p_T^{\rm trig}$ are caused by scale dependence of the parton fragmentation functions and the different parton flavor composition, in particular the ratio of quark and gluon jets. The parton fragmentation functions used in the calculation are given by parameterization. With finite values of initial jet energy, mass and other higher-twist corrections become important. The actual fragmentation functions will saturate and decrease for small values of z_T. The larger the E_T, the smaller the z_T of the saturation point.

Shown in Fig. 6 are the ratios of the hadron-triggered fragmentation functions in central Au + Au and $p+p$ collisions. In Au + Au collisions, hadrons are produced not only from jet fragmentation of the leading partons with reduced energy but also from the hadronization of the medium induced gluons. Normally, hadrons from medium induced gluons are softer and have a wider angular distribution than the hadrons from leading partons. One therefore has to define a bigger jet cone for the hadron-triggered effective fragmentation function. The softening of the effective fragmentation function is caused by the suppression of leading hadrons due to parton energy loss and the enhancement of soft hadrons from emitted gluons. Soft hadrons from emitted gluons become significant only at small z_T. At large z_T hadrons mainly come from fragmentation of the jet with reduced energy. Thus if one chooses large z_T, the near-side jet profile should not change. On the other hand, the back-side profile could change due to transverse momentum broadening.

6. High p_T azimuthal anisotropy

In non-central heavy-ion collisions, the parton energy loss has finite azimuthal anisotropy due to the azimuthal dependence of the path length of propagation. This will lead to a large azimuthal anisotropy of high-p_T hadron spectra [19] which has been observed by RHIC experiments [20]. After correction for two-particle correlations, the observed azimuthal anisotropy is consistent with that caused by parton energy loss [26,45]. The same energy loss also explains quantitatively the single hadron suppression and suppression of back-side jet correlations.

Since azimuthal anisotropy in hadron spectra is generated by the geometrical eccentricity of the dense medium, it is only sensitive to the evolution of the dense matter at very early time [46]. As the system expands, the geometry becomes more symmetric and thus loses its ability to generate spectra anisotropy. This is particularly true in late hadronic stage [47]. If there were no parton energy loss and no jet attenuation before a finite hadron formation time, then any anisotropy in spectra will be caused by the geometrical eccentricity at the time when hadron absorption starts. At this late time, a few fm$/c$ for example, the geometry is already quite symmetric and can no longer generate large anisotropy in the final hadron spectra. Therefore, the observed large azimuthal anisotropy at high p_T cannot be generated by hadronic absorption of jets in the late stage of the evolution. It should be noted that the parton energy loss considered so far is only sensitive to the gluon density of the medium. The question whether the medium under such a high parton density is deconfined quark–gluon plasma or hadronic matter cannot be addressed within jet quenching alone.

7. SPS data

The final piece of the evidence comes from experiments at SPS. Hadron spectra at this energy are very steep at high p_T and are very sensitive to initial transverse momentum broadening and parton energy loss [11]. However, the measured π spectra in central Pb + Pb collisions only show the expected Cronin enhancement [48,49] with no sign of significant suppression. More recent analyses of the Pb + Pb data at the SPS energy also show [50] that both same-side and back-side jet-like correlations are not suppressed, though the back-side distribution is broadened. Shown in Fig. 7 as a solid line is the energy dependence of the calculated single pion suppression factor at $p_T =$ 4 GeV$/c$ as compared to data at RHIC and SPS. The initial gluon density ρ_0 at $\tau_0 = 0.2$ fm$/c$ in the calculation of the parton energy loss in Eq. (6) is assumed to be proportional to the measured $dN_{\rm ch}/d\eta$ [51]. The measured multiplicity at SPS is only about 2.0 smaller than at the highest energy of RHIC. The calculated suppression increases more rapidly and reaches at 1 at the SPS energy. This is partly because of the Cronin effect which is much stronger at SPS and compensates some of the energy loss effect. However, the calculation is still about a factor of 3 smaller than the data. Similar results are reported in Ref. [24] when the same gluon density is used.

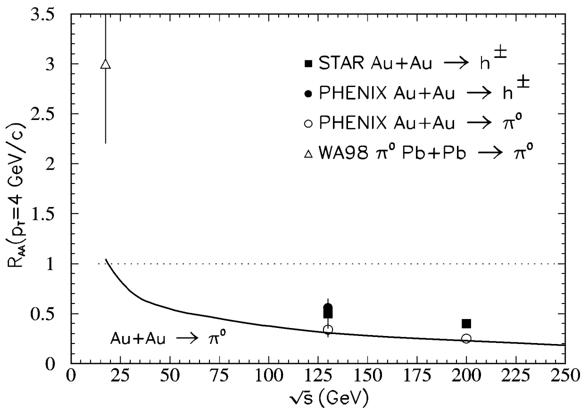

Fig. 7. The colliding energy dependence of the nuclear modification factor for single inclusive hadron spectra at fixed p_T in the most central Au + Au (or Pb + Pb) collisions as compared to the parton model calculation. The parton energy loss is assumed to be proportional to the measured charge multiplicity $dN_ch/d\eta$ while the medium formation time and lifetime of the medium are assumed to be the same. The data are from PHENIX [3], STAR [4] and WA98 [48].

There could be several reasons for such a big discrepancy between data and our calculation at SPS [11]. The initial formation time τ_0 could be much larger than at RHIC or the lifetime of the dense matter at SPS could be much shorter. Since a hadronic gas should have at least existed in Pb + Pb collisions at SPS and the particle density and duration of such a hadronic state should not be much different from that in Au + Au collisions at RHIC, hadronic rescattering or absorption should have significantly suppressed the pion spectra, were it responsible for most of the jet quenching at RHIC. Therefore, in any circumstances, the SPS data are not consistent with a hadronic absorption picture at RHIC.

Nevertheless, jet quenching at SPS energies still remains a less explored territory. As shown in Fig. 7, it will be important to have a few measurements between SPS and RHIC energy to explore the colliding energy dependence of jet quenching and find out whether there is any threshold behavior of jet quenching. By changing the colliding energy, one essentially changes the initial parton density without changing the initial medium size. This will allow one to observe the initial density dependence of jet quenching, obtain more information about formation time or lifetime of the medium, and search for critical behaviors that might be caused by phase transitions in the evolution of the dense medium.

8. Summary

This Letter has provided arguments and listed experimental evidence that the observed jet quenching or pattern of suppression of high-p_T hadron spectra in $\mathrm{Au}+\mathrm{Au}$ collisions at RHIC is caused mainly by parton energy loss, not hadron absorption in a hadronic medium. The estimated hadron formation time in jet hadronization is much longer than the typical lifetime of the dense matter and thus cannot be responsible for the observed jet quenching. The observed p_T and centrality dependence of jet quenching are not consistent with a hadronic absorption picture with a finite formation time that is smaller than the size of the medium. The measured high-p_T azimuthal anisotropy can only be caused by the geometrical anisotropy of the medium in a very early stage and thus cannot be due to hadronic rescattering. The most direct evidence for partonic energy loss and jet hadronization outside the medium is the universal same-side leading hadron correlations inside a jet in $p+p$, $d+\mathrm{Au}$ and $\mathrm{Au}+\mathrm{Au}$ collisions. Hadronic rescattering or absorption inside the medium would have destroyed the jet-like same-side correlation. Finally, the absence of jet quenching in $\mathrm{Pb}+\mathrm{Pb}$ collisions at SPS also indirectly proves that hadronic rescattering cannot be responsible for the observed jet quenching at RHIC.

A direct measurement of parton energy loss is also proposed which requires the reconstruction of the total energy of a jet that has a triggered hadron with a fixed value of p_T^{trig}. The difference between $\mathrm{Au}+\mathrm{Au}$ and $p+p$ measurements (plus p_T broadening due to initial multiple parton scattering) should be related to the averaged total energy loss for the jet whose leading parton produces the triggered hadron after energy loss. The measurement of softening of the effective hadron-triggered fragmentation function will further detail the pattern of energy loss and induced gluon emission. The importance of jet quenching studies at lower RHIC energies is also discussed.

It should be noted that there is always the possibility of some other mechanisms, such as hadronic absorption or the medium effect on the evolution of the fragmentation function [52] that could contribute to the observed jet quenching. However, the conclusion drawn in this Letter from the collective arguments and experimental evidences is that these cannot be the dominant cause for the observed pattern of jet quenching. Parton energy loss is the only natural explanation. Nevertheless, detailed understanding of the other possible contributions will help to understand the uncertainties in the extracted parton energy loss.

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References

[1] M. Gyulassy, M. Plumer, Phys. Lett. B 243 (1990) 432.
[2] X.N. Wang, M. Gyulassy, Phys. Rev. Lett. 68 (1992) 1480.
[3] PHENIX Collaboration, K. Adcox, et al., Phys. Rev. Lett. 88 (2002) 022301, nucl-ex/0109003;
PHENIX Collaboration, S.S. Adler, et al., nucl-ex/0304022.
[4] STAR Collaboration, C. Adler, et al., Phys. Rev. Lett. 89 (2002) 202301, nucl-ex/0206011;

STAR Collaboration, J. Adams, et al., nucl-ex/0305015.
[5] PHOBOS Collaboration, B.B. Back, et al., nucl-ex/0302015.
[6] STAR Collaboration, C. Adler, et al., Phys. Rev. Lett. 90 (2003) 082302, nucl-ex/0210033.
[7] X.N. Wang, Z. Huang, I. Sarcevic, Phys. Rev. Lett. 77 (1996) 231, hep-ph/9605213;
X.N. Wang, Z. Huang, Phys. Rev. C 55 (1997) 3047, hep-ph/9701227.
[8] PHENIX Collaboration, S.S. Adler, et al., nucl-ex/0306021.
[9] STAR Collaboration, J. Adams, et al., nucl-ex/0306024.
[10] PHOBOS Collaboration, B.B. Back, nucl-ex/0306025.
[11] X.N. Wang, Phys. Rev. C 61 (2000) 064910, nucl-th/9812021.
[12] M. Gyulassy, X.N. Wang, Nucl. Phys. B 420 (1994) 583, nucl-th/9306003.
[13] R. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne, D. Schiff, Nucl. Phys. B 484 (1997) 265, hep-ph/9608322.
[14] B.G. Zakharov, JETP Lett. 63 (1996) 952, hep-ph/9607440.
[15] M. Gyulassy, P. Levai, I. Vitev, Phys. Rev. Lett. 85 (2000) 5535, nucl-th/0005032.
[16] U.A. Wiedemann, Nucl. Phys. B 588 (2000) 303, hep-ph/0005129.
[17] X.F. Guo, X.N. Wang, Phys. Rev. Lett. 85 (2000) 3591, hep-ph/0005044;
X.N. Wang, X.F. Guo, Nucl. Phys. A 696 (2001) 788, hep-ph/0102230.
[18] E. Wang, X.N. Wang, Phys. Rev. Lett. 89 (2002) 162301, hep-ph/0202105.
[19] X.N. Wang, Phys. Rev. C 63 (2001) 054902, nucl-th/0009019.
[20] C. Adler, et al., Phys. Rev. Lett. 90 (2003) 032301.
[21] X.N. Wang, Nucl. Phys. A 715 (2003) 775, hep-ph/0301196.
[22] S.Y. Jeon, J. Jalilian-Marian, I. Sarcevic, Phys. Lett. B 562 (2003) 45, nucl-th/0208012.
[23] B. Muller, Phys. Rev. C 67 (2003) 061901, nucl-th/0208038.
[24] I. Vitev, M. Gyulassy, Phys. Rev. Lett. 89 (2002) 252301.
[25] T. Hirano, Y. Nara, nucl-th/0301042.
[26] X.N. Wang, nucl-th/0305010.
[27] M. Gyulassy, I. Vitev, X.N. Wang, Phys. Rev. Lett. 86 (2001) 2537, nucl-th/0012092.
[28] PHENIX Collaboration, K. Adcox, et al., Phys. Rev. Lett. 88 (2002) 022301, nucl-ex/0109003.
[29] STAR Collaboration, C. Adler, et al., Phys. Rev. Lett. 87 (2001) 182301, nucl-ex/0107003;
STAR Collaboration, J. Adams, et al., nucl-ex/0306007.
[30] PHENIX Collaboration, S.S. Adler, et al., nucl-ex/0305013.
[31] Yu. Dokshitzer, V.A. Khoze, A.H. Mueller, S.I. Troyan, Basics of Perturbative QCD, Editions Frontiéres, Gif-sur-Yvette, 1991.
[32] B.Z. Kopeliovich, Phys. Lett. B 243 (1990) 141.
[33] U. Amaldi, K.R. Schubert, Nucl. Phys. B 166 (1980) 301;
X.N. Wang, Phys. Rev. D 43 (1991) 104.
[34] S.J. Brodsky, P. Hoyer, Phys. Lett. B 298 (1993) 165, hep-ph/9210262.
[35] HERMES Collaboration, A. Airapetian, et al., Eur. Phys. J. C 20 (2001) 479, hep-ex/0012049;
HERMES Collaboration, V. Muccifora, Nucl. Phys. A 715 (2003) 506, hep-ex/0106088.
[36] F. Arleo, hep-ph/0306235.
[37] T. Falter, W. Gassing, K. Gallmeister, U. Mosel, nucl-th/0303011.
[38] E. Wang, X.N. Wang, Phys. Rev. Lett. 87 (2001) 142301.
[39] C.A. Salgado, U.A. Wiedemann, Phys. Rev. Lett. 89 (2002) 092303.
[40] PHENIX Collaboration, K. Adcox, et al., Phys. Rev. Lett. 86 (2001) 3500, nucl-ex/0012008.
[41] PHOBOS Collaboration, B.B. Back, et al., Phys. Rev. C 65 (2002) 061901, nucl-ex/0201005.
[42] U.A. Wiedemann, Nucl. Phys. A 690 (2001) 731, hep-ph/0008241.
[43] I.P. Lokhtin, A.M. Snigirev, Phys. Lett. B 567 (2003) 39, hep-ph/0303121.
[44] S. Pal, S. Pratt, nucl-th/0305082.
[45] E.V. Shuryak, Phys. Rev. C 66 (2002) 027902, nucl-th/0112042.
[46] J.Y. Ollitrault, Phys. Rev. D 46 (1992) 229.
[47] P.F. Kolb, J. Sollfrank, U.W. Heinz, Phys. Rev. C 62 (2000) 054909, hep-ph/0006129.
[48] WA98 Collaboration, M.M. Aggarwal, et al., Phys. Rev. Lett. 81 (1998) 4087, nucl-ex/9806004;
WA98 Collaboration, M.M. Aggarwal, et al., Phys. Rev. Lett. 84 (2000) 578, Erratum;
WA98 Collaboration, M.M. Aggarwal, et al., Eur. Phys. J. C 23 (2002) 225, nucl-ex/0108006.
[49] X.N. Wang, Phys. Rev. Lett. 81 (1998) 2655, hep-ph/9804384.
[50] CERES/NA45 Collaboration, G. Agakichiev, et al., nucl-ex/0303014.
[51] PHOBOS Collaboration, B.B. Back, et al., Phys. Rev. Lett. 88 (2002) 022302, nucl-ex/0108009.
[52] B.G. Zakharov, JETP Lett. 76 (2002) 201, Pis'ma Zh. Eksp. Teor. Fiz. 76 (2002) 236, hep-ph/0207206.